TNO Institute for Human Factors IZF

TNO Defence Research

TD 94-0048 IV

Fax +31 3463 5 39 77
Telephone +31 3463 5 62 11

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A.H. Wertheim
R. Heus
T.G.M. Vrijkotte

ENERGY EXPENDITURE, PHYSICAL WORK LOAD AND POSTURAL CONTROL DURING WALKING ON A MOVING PLATFORM

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Authors:	Dr. A.H. Wertheim, Drs. R. Heus, and Drs. T.G.M. Vrijkotte
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SUMMARY

An experiment was performed in which subjects were required to walk on a treadmill inside a moving ship motion simulator (SMS). Ventilatory measures of energy consumption, heart rate, and measures of postural control were taken and compared to a condition in which the SMS did not move. Eleven SMS movement conditions were investigated, two of which consisted of pure one dimensional sinusoidal movements (vertical motion or roll), two of simulated ship movements, and seven of various combinations of (large or small) vertical, pitch and roll movements, derived from these simulated ship motion profiles. The results showed that energy expenditure was largest in conditions which included either large pitch movements, or large roll components in combination with pitch. Energy expenditure was intermediate in all other conditions which included large roll movements. Effects of the particular vertical motions used in the present study, were not observed. In this particular study, physiological task load (expressed in terms of ventilatory parameters) was shown to increase on average with 15% during SMS movements. Heart rate appeared to be a less reliable measure of energy expenditure. Movement induced interruptions (MII's) of the walking task—a measure of postural control—were most frequent in conditions which included a large roll component. The relevance of this work with respect to the development of work load criteria at sea, for the estimation of a crew's operational capacity, and for ship building design are given, together with some recommendations for further research.

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TNO Technische Menskunde[1]
Soesterberg

Energieverbruik, fysieke arbeidsbelasting en handhaven van het evenwicht tijdens het lopen op een bewegend platform

A.H. Wertheim, R. Heus en T.G.M. Vrijkotte

SAMENVATTING

Een experiment werd uitgevoerd waarbij proefpersonen moesten lopen op een tredmolen die zich in een bewegende scheepsbewegingssimulator (SMS) bevond. Ventilatoire parameters, indicatief voor het energieverbruik van het lichaam (metabolisme), werden bepaald, evenals hartslag frequentie, arbeidsbelasting, en een parameter welke aangeeft in hoeverre de bewegingen van de simulator interfereren met het soepel handhaven van het evenwicht (MII's). Elf typen beweging van de SMS werden onderzocht en vergeleken met een conditie waarin de SMS niet bewoog. Twee bewegingen waren puur sinusoidaal (dompen of slingeren), twee bewegingen bestonden uit een gesimuleerd scheepsbewegingsprofiel, en zeven bewegingen bestonden uit verschillende combinaties van domp-, stamp- en/of slingerbewegingen, allen afgeleid van het gesimuleerde scheepsbewegingsprofiel. De resultaten toonden dat het energieverbruik van het lichaam het grootst was tijdens SMS bewegingen die ofwel een grote stamp beweging includeerden, ofwel een grote slingerbeweging in combinatie met een stampbeweging. Een iets geringere toename in energieverbruik werd geconstateerd in alle andere condities waarin een grote slingerbeweging voorkwam. De in deze studie gehanteerde dompbewegingen hadden geen effect. In vergelijking met taakuitvoering in de stilstaande SMS, was de arbeidsbelasting tijdens bewegingen van de SMS in de onderhavige studie, gemiddeld 15% hoger. Houdingsevenwicht werd het vaakst verstoord in bewegingscondities met een grote slingercomponent. De relevantie van dit type onderzoek wordt aangegeven met betrekking tot het ontwikkelen van criteria voor toegestane arbeidsbelasting aan boord van schepen, voor het inschatten van de operationele inzetbaarheid van bemanningen, en voor het ontwerpen van schepen. Mogelijkheden voor verder onderzoek worden belicht.

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[1]Per 1 februari 1994 is de naam Instituut voor Zintuigfysiologie TNO gewijzigd in TNO Technische Menskunde.

1 INTRODUCTION

At sea ship movements, such as pitch, roll, or vertical movements, may be quite strong, especially with relatively small vessels. Working aboard such a moving ship is likely to be more demanding than when the same job is performed ashore, because of the extra attentional and muscular efforts required to maintain one's balance. Therefore, it is likely that tasks which require motor activity or perceptual-motor skills may become very fatiguing, especially when they must be performed while standing or walking. Although some attention has been given to these problems (see for a review Colwell, 1989), no attempts have been made to quantify these motion induced task strains, or to correlate them to particular ship motion parameters. There is, however, a need for such information. Without it we cannot establish criteria for what kind of work aboard ships may be considered as reasonable and what not, in terms of workload. Such information may also be helpful in estimating the general operational capability of a ships crew at various sea states. As such it could be relevant also for ship building design. It was the purpose of the present research to make a first step in these directions by developing a general method that allows for the measurement of work load during task performance in terms of physiological energy consumption.

In a first study carried out at the TNO Institute for Human Factors (Wertheim et al., 1993) we investigated the feasibility of measuring the energy consumption of subjects during walking on a moving platform, with a variety of physiological measures. The results revealed that the simple task of walking on a moving platform could already be shown to require more energy when the platform moved sinusoidally (.125 Hz) in pitch or roll direction (with an amplitude of 5 deg), than when it remained stationary or moved only in vertical direction (with a 30 cm amplitude). Walking during pitch and roll took approximately 20% more energy than walking on a non-moving floor (no difference in energy consumption was found between free walking and walking on a treadmill).

This research showed that it is indeed feasible to measure the differences in human energy consumption requirements, associated with task performance on a moving platform. But if we want to establish work load criteria, this is not enough, because that implies that we should know how much this energy consumption is, relative to the total capacity for energy expenditure available to a subject. In other words, we need to ask what is the energy requirement of a task expressed as a percentage of total energy capacity of the subject. The elevation of the energy consumption, as caused by ship motions, should not exceed 40% of the total work capacity of the subjects. Otherwise, the demand for aerobic power is too high for steady state work during a normal eight hour working day (Evans et al., 1980; Åstrand & Rodahl, 1986). If we had wanted to express energy consumption this way, we should have measured this maximum capacity for energy expenditure of each subject, prior to the experiment. This is the first purpose of the experimental study reported here.

Since the earlier study was only a feasibility study to test if differences in energy expenditure could indeed be measured with relatively small platform movements, we cannot from that study draw conclusions that would generalize to real ship movements. Real ship motions usually consist of particular combinations of such motions and they are often not as smooth and as predictable as the sinusoidal platform motions used in this first experimental study. Thus, the second purpose of the experiment reported here was to obtain empirical data that have more relevance to reality. For this reason the present experiment uses real ship motions, or the vertical, roll and pitch components of such real ship motions in a variety of combinations (for purposes of comparability with the earlier study, we included some simple sinus movement conditions also).

Finally, a question was raised in the discussion of the earlier study: do ship motions interfere with the task of walking itself, and if so, is there a difference between pitch, roll and vertical motions? The point is that interruptions of postural control during walking (or, to be more precise, recuperation from them) may explain the higher energy consumption during walking on a moving platform. If so, there should have been more such "motion induced interruptions" (MII's) during pitch and roll, than during vertical motions of the platform, or during platform stationarity. The third purpose of the present study was to investigate this issue with the help of a procedure for scoring MII's.

2 MATERIALS AND METHODS

In this study we investigated human energy consumption while walking on a treadmill, during 11 types of platform motion, 9 of which represented or were components of real ship motions, and two were sinusoidal only. In an additional control condition the platform remained stationary.

2.1 **Ship Motion Simulator (SMS)**

As in the earlier study, platform motions were generated with the ship motion simulator (SMS) of the TNO Institute for Human Factors. The SMS consists of a large cabin (length 4.5 m, width 2.4 m and height 2.6 m) placed on top of a hydraulic cylinder system. The SMS can move with three degrees of freedom: vertical motion (range ± 0.5 m), pitch (range ± 20°) and roll (range ± 15°). The cabin floor is positioned 2 m above the pitch and roll axes, which implies that subjects inside the cabin may experience additional vertical and horizontal linear motion during roll and pitch movements of the SMS, dependent on their position inside the cabin. In the present experiment the subjects inside the cabin walked on a treadmill, which was placed on the floor of the cabin against one of its longer side walls, i.e. parallel to the length axis of the cabin, but approximately 0.5 m off centre. Walking speed on the treadmill was set at a constant value of

1 m/s. The walls of the cabin were soft padded, and the treadmill was equipped with handrails on both sides, but subjects on the treadmill were asked not to use them for support unless they felt they needed them to prevent falling. Part of the apparatus for measuring and analysing the ventilatory parameters (see § 2.7.1) was also placed inside the cabin. Closed circuit video and audio connections allowed continuous contact with the subjects, and the whole experiment was recorded on videotape.

2.2 Motion profiles

As mentioned before, two different kinds of cabin motion profiles were applied: simulated ship motions, and pure sinusoids. When external measurements were taken to obtain exact measures of the actual motion parameters of the SMS in all conditions (see Appendix A), it appeared that with a zero input signal there was a slight offset in the pitch channel. As a result, subjects on average (i.e. across all conditions, during the whole experiment) walked one degree "uphill".

2.2.1 *Simulated ship motion profiles*

A motion profile measured aboard a ship at sea was obtained from the Naval Biodynamics Laboratory (NBDL), New Orleans, USA (file code: nbdl501) in the form of an multi-channel ASCII file containing vertical, pitch and roll movements. RMS values were 0.725 m in vertical motion, 0.91° in pitch, and 2.68° in roll.

The complete original 5 Hz ship motion file from NBDL was interpolated (linearly) to obtain a 25 Hz file. This was necessary because a 5 Hz resolution yielded too large discrete steps in the control signals to the SMS hydraulics, causing shocks and vibrations.

Because of the physical limitations of the SMS, a rescaling of the vertical motion channel, i.e. a vertical motion compression, was necessary, because the original vertical motion excursions of the ship (which included peaks of several meters) were beyond the capacity of the SMS. To remain within the limits of the SMS we had to apply a compression factor of 0.16.

Only the first 580 s of the NBDL file were used, after which the same file was read out again (cyclic readout). On this segment of the final motion profile the RMS values were 0.146 m in vertical motion, 1.36° in pitch, and 3.44° in roll. Thus for this segment of the NBDL file, RMS values were somewhat larger than when calculated across the whole NBDL file for pitch and roll, and considerably smaller for vertical (because of the above mentioned compression).

These values reflect the input movement parameters. The actual SMS motion parameters, as measured externally, are listed in Appendix A for all conditions (see Table I below).

2.2.2 *Sinusoidal motion profiles*

Sinusoidal SMS motions were computer calculated (at 25 Hz sample frequency). For vertical motions a frequency of 0.125 Hz and an amplitude of 0.45 m was chosen, which is as close to the maximum capacity of the SMS as possible. Sinusoidal motion in roll was chosen such that its RMS value was about the same as that of the much less predictable real ship roll motion. This yielded a sinusoidal roll frequency of 0.14 Hz with an amplitude of 5.3° and a 3.77° RMS value. (These are input movement parameters. The actual movement characteristics of the SMS in the sinusoidal vertical and roll movement conditions are slightly different; see Appendix A.) Thus, a comparison between predictable sinusoidal and unpredictable real ship motions was made possible, that is, for vertical and roll movements. For pitch no such comparison was included in the design (because of time limitations we had to restrict the experiment to 12 measurement conditions).

2.2.3 *Parasitical SMS movements*

Theoretically, a vertical motion correction should be applied, to correct for unwanted parasitical vertical motion components, caused by the vertical displacement of the SMS cabin during pitch and roll (because the axis of rotation is significantly below the floor level of the cabin). Strictly speaking, this artefactual vertical motion component can be calculated for each roll and pitch value, and should then be subtracted from the concurrent (compressed) vertical motion input signal to the SMS. Due to a calculation error (detected only after completion of the experiment) these correction were not properly carried out. Hence, the vertical components of the SMS movements as experienced by our subjects, were slightly different from what we intended them to be. However, these parasitical movements are very small as compared to the main vertical components applied (see Appendix A). Their negligibility is illustrated by the fact that both in the earlier study and in the present one (see chapter 3 below) we observed no effects even of much stronger vertical SMS motion, on any ventilatory parameter or on heart rate.

It should be noted that the SMS also yields a parasitical translatory motion during pitch and roll motions. This cannot be corrected, because the mechanical construction of the SMS does not allow for translatory cabin motion (apart from parasitical artifacts). With a sinusoidal roll at 0.125 Hz and 5° amplitude, this parasitical translatory force peaks to about 0.2 m/s^2.

2.3 Conditions

The experiment included 12 conditions:

Condition 1: Cabin remains stationary
Condition 2: Simulated ship motion in Vertical motion, Pitch, and Roll
Condition 3: Sinusoidal Vertical motion: freq 0.125 Hz; ampl 0.45 m.
Condition 4: Simulated ship motion only in Pitch
Condition 5: Simulated ship motion only in Roll
Condition 6: Simulated ship motion only in Roll, but the original Pitch input is now used as input for the Roll channel of the SMS. (Hence in this condition Roll motions are weaker than in condition 5)
Condition 7: Simulated ship motion only in Pitch, but the original Roll input is now used as input for the Pitch channel of the SMS. (Hence in this condition Pitch motions are stronger than in condition 4)
Condition 8: Simulated ship motion only in Vertical motion and Pitch
Condition 9: Simulated ship motion only in Vertical motion and Roll
Condition 10: Simulated ship motion only in Pitch and Roll
Condition 11: Simulated ship motion in Vertical motion, Pitch and Roll, but the original Pitch input is now used as input for the Roll channel of the SMS, and the original Roll input is now used as input to the Pitch channel of the SMS. (Hence this condition is similar to condition 2, but now Roll motions are weaker and Pitch motions stronger)
Condition 12: Sinusoidal Roll: freq 0.14 Hz; RMS 3.77°

Table I summarizes these 12 conditions to allow for a quick review of the magnitudes of the pitch and roll components in each condition.

Table I Summary of experimental conditions.

COND	MOTION TYPE	VERTICAL MOTION	PITCH	ROLL	CODE
1	stationary	-	-	-	**s**
2	ship	yes	small	large	**hpR**
3	sinus	yes	-	-	**H(sin)**
4	ship	-	small	-	**p**
5	ship	-	-	large	**R**
6	ship	-	-	small	**r**
7	ship	-	large	-	**P**
8	ship	yes	small	-	**hp**
9	ship	yes	-	large	**hR**
10	ship	-	small	large	**pR**
11	ship	yes	large	small	**hPr**
12	sinus	-	-	large	**R(sin)**

2.4 Subjects

Six healthy male and six healthy female subjects participated in this study as paid volunteer subjects The study was formally approved by the committee for the judgement of experimental ethics and the protection of subjects, of the TNO Institute for Human Factors. The subjects were informed about the purpose and procedures of the study and signed an informed consent statement prior to participation. Before they were allowed to participate, all subjects underwent a medical examination, designed especially to guard against medical problems which might otherwise result from the maximum energy expenditure test (we did in fact reject one candidate subject on the basis of this examination).

2.5 Measurement of maximum energy expenditure

In this study the maximum amount of energy consumption was measured for each subject prior to the experiment, which enabled expression of the physiological indices of energy consumption as a percentage of this maximum.

One or two days before the start of the experiment each individual subject participated in a maximum energy expenditure test, which consisted of a well known standard performance procedure on the treadmill (running until exhaustion on a treadmill placed in sloping position, the slope increasing at regular intervals). The test allows for the measurement of individual maximal work capacity (expressed in terms of maximum oxygen consumption, $\dot{V}O_{2max}$ and maximum heart rate, HR_{max}), and represents what is known as a modified Balke protocol on a treadmill (see Balke and Ware 1959 for details). The apparatus used for the analysis of breathing air and heart rate measurements was the same as used in the experiment itself (see § 2.7.1). Individual scores obtained on this maximal work capacity test are reported in Table II, together with other anthropometric and physiological data of the subjects.

Table II Anthropometric and biological characteristics, $\dot{V}O_{2}max$ and HR_{max} for all subjects as measured on the maximal work capacity test.

Subject No.	Sex	Age Year	Body Mass kg	Body Fat % [1]	Height cm	$\dot{V}O_{2}max$ $ml \cdot min^{-1} \cdot kg^{-1}$	HR_{max} $beats \cdot min^{-1}$
1	M	24	68.9	8.0	190	65.8	185
2	M	34	93.8	22.1	182	51.9	176
3	F	22	60.3	17.4	163	57.4	198
4	M	33	59.7	12.5	178	59.6	191
5	F	25	55.3	25.9	160	34.8	212
6	F	20	56.6	19.4	167	41.1	193
7	M	23	68.7	9.8	190	66.3	190
8	F	21	65.0	28.4	165	40.2	205
9	F	20	61.9	27.8	167	41.1	196
10	M	22	88.1	18.0	185	51.3	202
11	F	19	65.0	24.7	179	42.0	188
12	M	3[illegible]	68.3	13.0	185	64.1	175
mean		24.5	67.6	18.9	175.9	51.3	192.6
SD		5.2	11.8	7.0	10.9	11.3	11.0

[1] Measured by the skinfold technique of four skinfolds (triceps, biceps, subscapular and suprailiac) (Durnin & Womersley, 1974).

2.6 Experimental design

Each condition of the actual experiment lasted for approximate'y 15 minutes. After subjects were instructed on how to walk on the treadmill and how to breath trough the mouthpiece—attached with a flexible tube to the ventilatory analysis apparatus inside the SMS—the door of the SMS cabin was closed, and for the first 5 minutes measurements were taken but not recorded (the apparatus for the respiratory analysis was allowed to reach stable levels). Thus, experimental measurements were recorded only during the last 10 minutes of each condition. Apart from the medical test and the maximum energy expenditure test, which were carried out prior to the actual experiment, the complete experiment itself took two days, during each of which six conditions were measured with two alternating subjects. The order of presentation of conditions was randomized within and between subjects (see Appendix B).

2.7 **Dependent variables**

2.7.1 *Measures of energy consumption*

Ventilatory parameters

Oxygen consumption ($\dot{V}o_2$), carbon dioxide production ($\dot{V}co_2$) and ventilation ($\dot{V}_E$) of the subjects were measured with an Oxycon Σ (Mijnhardt BV) in the mixing chamber mode. The exhalation air of the subjects, breathing through a mouth piece, was conveyed to the Oxycon (placed inside the SMS cabin at a distance of approximately 2 m behind the subject) with a flexible tube, where it was analyzed on line. The data from the analysis were sent to a computer placed in the control room of the SMS, where they were displayed and monitored continuously.

The ventilatory parameters were used to calculate the metabolism score (ISO 8996)—which is a standard measuring unit of human energy consumption—with the following formula:

$$\text{Metabolism (Watts)} = \frac{(0.23 * \text{RE} + 0.77) * 21.14 * \dot{V}O_2}{60}$$

RE = respiratory equivalent (= $\dot{V}co_2/\dot{V}o_2$). A RE value higher than 1 indicates hyperventilation (Fox & Mathews, 1981).

Measure of physiological work load

A standard measure of physiological workload is $\dot{V}o_2$ expressed as percentage of $\dot{V}o_{2max}$ (as measured by the standard maximal test on the treadmill with the Balke protocol, see above). This measure indicates the amount of energy consumed given the maximum capacity of energy consumption, characteristic of the subject. As mentioned before, according to international standards, this percentage is not supposed to increase over 40% during a normal working day (Pandolf et al., 1977).

Heart rate

Heart rate was monitored with a Sporttester (Polar Electro OY) with an electrode belt around the chest of the subjects. The electrode belt was also connected to the Oxycon which also sent these signals to the computer and monitor in the control room for on line information about the heart rate.

2.7.2 *Measures of postural control (MII's)*

Subjects were asked to walk continuously on the treadmill, at a speed of 1 m/s, without using the handrail for support. If, however, the subjects misplaced a step

—usually because of the movements of the SMS—a problem with the maintenance of balance might occur. Such instances were easily visible on the video screen. On occasions, subjects also had to grip one of the hand rails for support. Such motion induced interruptions (MII's) were scored during the experiment by two observers: the subject him/her self inside the SMS (using a small hand held push button), and an independent observer in the control room, who watched the on line video image. Since during one experimental day two subjects participated in alternating order between conditions, one subject was always available outside the SMS to act as the second MII rater. Instances on which an MII was scored were recorded with two counters (one for each observer). The counter displays were mixed in the videotaped image, enabling easy post hoc analysis of MII's. The mean of both scores across the 10 minutes experimental period within each condition was used as a measure of MII (for interrate reliability, see § 3.4).

2.8 Statistics

For each ventilatory and heart rate parameter, the data were (after checking for homogeneity of variance) subjected to an analysis of variance with conditions and gender as independent variables (Systat software package). The differences between conditions were also analyzed for significance with a Tukey post hoc test (Winer et al., 1991) ($p<.05$).

To investigate whether there were differences between conditions with respect to MII's, these differences had, however, to be tested with a multitude of paired comparison t-tests (also using Systat software), because non homogeneity of their variance prevented the use of analysis of variance.

3 RESULTS

Due to a technical failure of the ventilatory analysis apparatus data were lost for the last six conditions of subject 11 and of the last two conditions of subject 12. For this reason, none of the data of these subjects could be included in the statistical analysis. Hence the results are given only for 10 subjects.

3.1 Measures of energy consumption

We did not observe a significant main effect of gender on any of the ventilatory measures for energy consumption. Neither was there evidence for any interaction between gender and movement conditions. None of the other anthropometric and biological characteristics (Table II) appeared to have any significant effect either.

3.1.1 *Ventilatory parameters*

Oxygen consumption

Between conditions, oxygen consumption ($\dot{V}o_2$) differed significantly. Highest oxygen consumption happened in conditions hPr, hpR, P and pR. These are the conditions that include either a large pitch component or a large roll component in combination with pitch (see Table I). Least oxygen consumption was observed in conditions s, H(sin), hp, p and r, which are the conditions that do not include any large pitch or roll components (see Table I). This means that if the SMS moves with only small pitch and/or roll motions, oxygen consumption does not statistically differ from the stationary condition. When all conditions are rank ordered (as we did with the figures in this report), we find that the mid position between these high and low energy expenditure condition clusters, is taken by conditions R, hR and R(sin), that is by the group of conditions with large roll but no pitch components.

This particular pattern of results remained identical when the $\dot{V}o_2$ values were normalized with respect to body weight (Fig. 1).

In general, the results can be summarized as followings:
1 Most energy consumption was required whenever SMS motion included both a pitch and a roll component. The only exception was the condition with only a large pitch component.
2 The conditions with intermediate energy requirements were those with a large roll component without any pitch.
3 Least energy is required when SMS motion included only small pitch and/or roll components. These conditions do not even differ (statistically) from the stationary control condition.
4 There appears to be no particular effect of vertical motion, that is not for those vertical motion values used in the present study.
5 It seems that the only two conditions with all three components, hPr and hpR, rank highest (although they are not statistically different from the two next highest conditions P and pR). This at least suggests that, even though vertical motion in itself may have little effect, it may enhance energy consumption requirements when it is combined with both pitch and roll, as is usually the case in real ship movements.

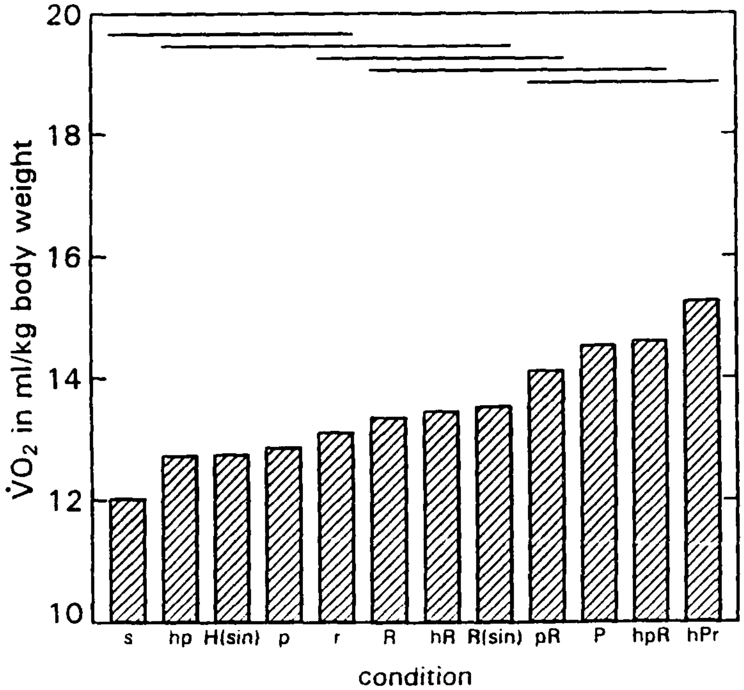

Fig. 1 Group mean values of $\dot{V}o_2$ per kg body weight during different SMS movement condition. Conditions connected with a horizontal line in the upper part of the figure, do not differ significantly from each other.

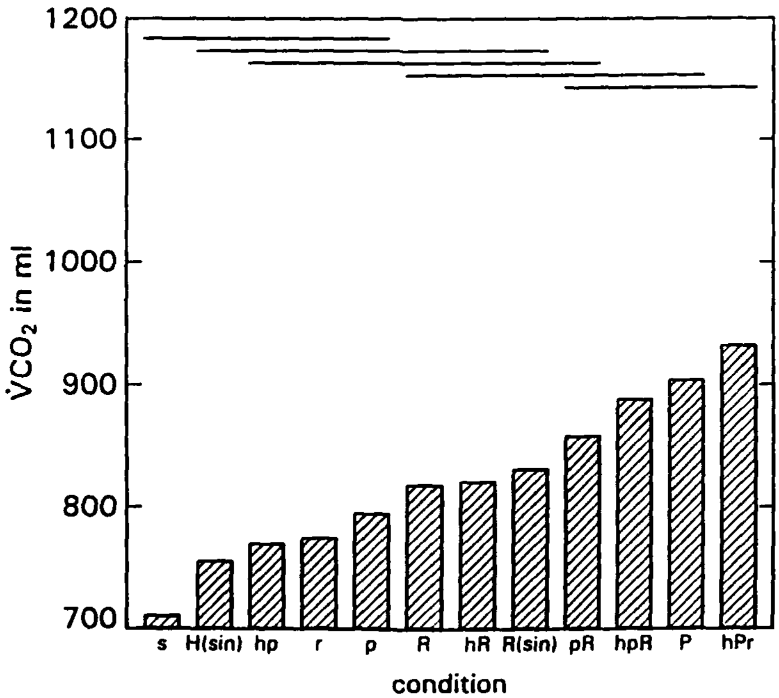

Fig. 2 Group mean values of $\dot{V}co_2$ during different SMS movement conditions. Conditions connected with a horizontal line in the upper part of the figure, do not differ significantly from each other.

Carbon dioxide production

For carbon dioxide production ($\dot{V}co_2$) during walking on a moving platform the results are similar to those of $\dot{V}o_2$ consumption: the highest values were again observed in the conditions hPr, hpR, P and pR, the lowest values in conditions s, H(sin), hp, r and p, and the intermediate conditions were again conditions R, hR and R (Fig. 2).

Ventilation

The same pattern of results was also observed with the ventilation parameter $\dot{V}_E$. Across the four conditions with the highest ventilation values mean ventilation was 24.0 $l \cdot min^{-1}$. Mean ventilation across the five lowest value conditions was 20.6 $l \cdot min^{-1}$.

RE values were never larger than 1. Hence, there was no indication of hyperventilation in any of the conditions (RE, mean values ± SD were .90 ± .05).

Metabolism

The metabolism index again showed exactly the same pattern of results (Fig. 3). The mean of the metabolism index across the conditions with the highest values was 342 Watts. For the conditions with the lowest values, it was 296 Watts.

3.1.2 *Physiological work load*

When $\dot{V}o_2$ consumption is expressed as a percentage of $\dot{V}o_{2max}$ as observed in the prior maximal test, the results are again the same (Fig. 4).

Physiological workload for the most demanding conditions (hPr, P, hpR and pR) was on average 29.9% of total capacity. For the least demanding conditions (s, H(sin), hp, p and r) it was 25.9% of total capacity. On average, walking on the treadmill in one of the most demanding conditions required 22% more energy than in the control condition s, where the SMS remained stationary. Although this is a statistically significant increase, it is only an average. If we compare the stationary control condition with the single most demanding condition hPr, the increase in task demand becomes 27.9%.

3.1.3 *Heart rate*

Apart from a main effect of gender, none of the anthropometric and biological characteristics from Table II had any significant effect, or interacted with any other variable, on the heart rate parameter. The effect of gender—male subjects had lower heart rates than female subjects—is usually observed in research where heart rate is used as a dependent variable (see Wertheim et al., 1993).

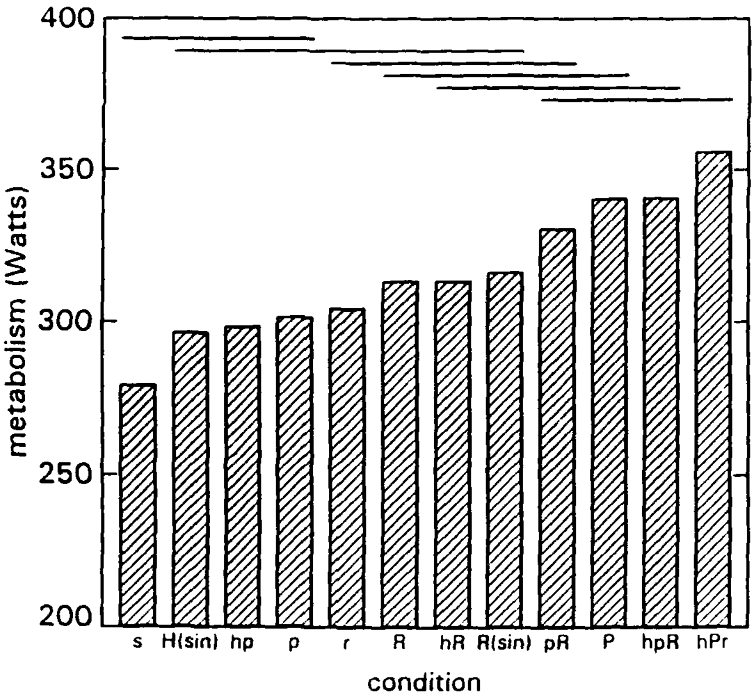

Fig. 3 Group mean values of metabolism during different SMS movement conditions. Conditions connected with a horizontal line in the upper part of the figure, do not differ significantly from each other.

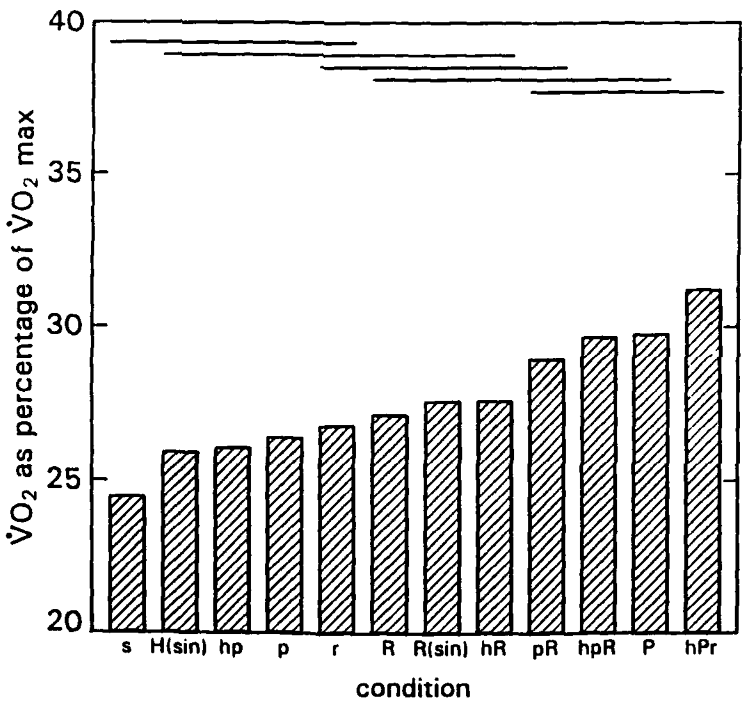

Fig. 4 Group mean values of $\dot{V}o_2$ consumption as a percentage of the $\dot{V}o_{2max}$ of during different SMS movement conditions. Conditions connected with a horizontal line in the upper part of the figure, do not differ significantly from each other.

However, as can be seen from Fig. 5, only the highest and lowest heart-rate conditions differed significantly from each other. In general, the differences between conditions were smaller than in the prior study.

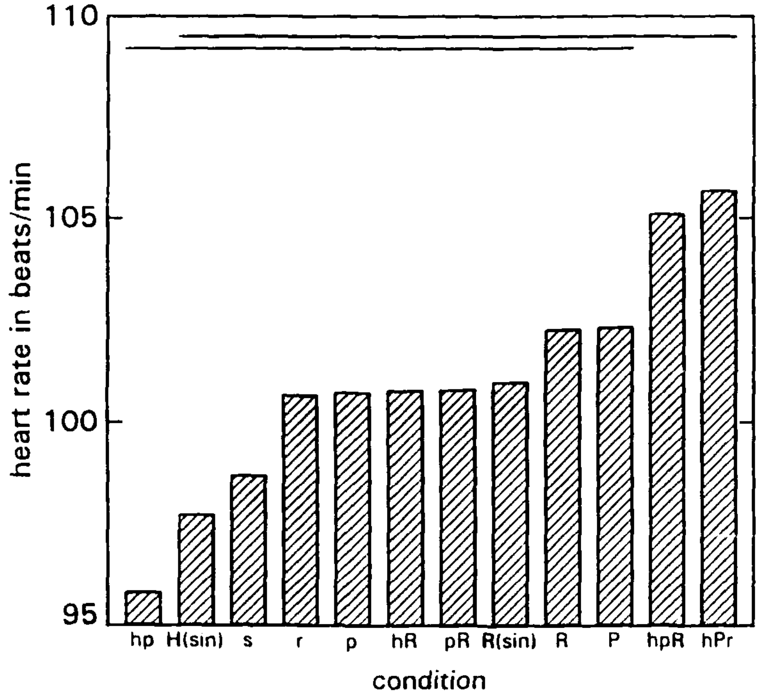

Fig. 5 Group mean values of heart rate in beats per minute during different SMS movement conditions. Conditions connected with a horizontal line in the upper part of the figure, do not differ significantly from each other.

Nevertheless, although we can only speak of a trend, the two conditions which showed the highest heart rate (hpR and hPr) happened to be among the three conditions that also required most energy in terms of the ventilatory parameters.

3.1.4 *Predictability of SMS movements*

Energy consumption, as measured by ventilatory parameters, appeared to be the same with predictable and unpredictable SMS motion parameters. This was clearly observed for roll motion (no difference between conditions R and R(sin). It was suggested also for vertical motion, because condition H(sin)—in which predictable vertical motion was present exclusively—did not differ from condition hp, which included unpredictable vertical motion (condition hp also included a small pitch movement, but unpredictable vertical motion-only conditions were not included in the design). However, with respect to vertical motion, a better comparison would have been between H(sin) and a condition that included unpredictable vertical motion with larger magnitudes.

3.2 Measures of postural control (MII's)

Across all conditions and subjects, the correlation between the ratings of the two observers who scored the MII's (the subject inside the SMS and the one outside the SMS, who watched the video image in the control room) was very high (r = 0.92), which indicates that the reliability of the scoring procedure was high.

On first glance, it appeared that most motion induced interruptions (MII's) happened during conditions R and R(sin), i.e. in conditions where the SMS made only large roll movements (Table III).

Table III Motion induced interruptions during a 10 minutes period for the different moving platform conditions.

	CONDITION											
	1	3	4	8	6	11	7	9	10	2	12	5
MII's	.00	.03	.11	.23	.44	.49	.71	2.63	2.73	3.80	4.23	5.31

However, the statistical analysis showed that conditions R and R(sin) did not differ significantly from any of the other conditions, while some of those other conditions did in fact differ significantly from each other (for example, conditions hR, pR and hpR were significantly different from conditions s, H(sin), p, hp, r, hPr and P). This curious result stems from the use of many paired comparison t-tests and appeared due to extremely high MII-scores especially in condition R and R(sin) of one subject (subject no. 3). Inspection of the video tape revealed, that the instructions for identifying MII's to both subject 3 (inside the SMS) and to subject 4 (who acted as MII rater in the control room), had apparently been misunderstood. In stead of scoring instances in which the subject inside the SMS made a misstep that threatened balance control, an MII was scored also whenever the subject touched one of the hand rail bars with her elbow. This happened fairly regularly with subject 3 (not with subject 4), especially in conditions where the SMS made large roll motions. These roll motions caused a kind of regular swaying of the subject, enough for her to touch the handrail lightly with her elbow almost each time the SMS reached its maximum roll. But almost in all these instances, no visible evidence of a possible disturbance in postural control was present, and it was obvious from visual inspection of the tape, that the touching of the handrail had no support function. Therefore, we felt justified to correct the MII results for these extremely high scores, by removing the results of subject 3 from analysis. The remaining data are presented in Fig. 6.

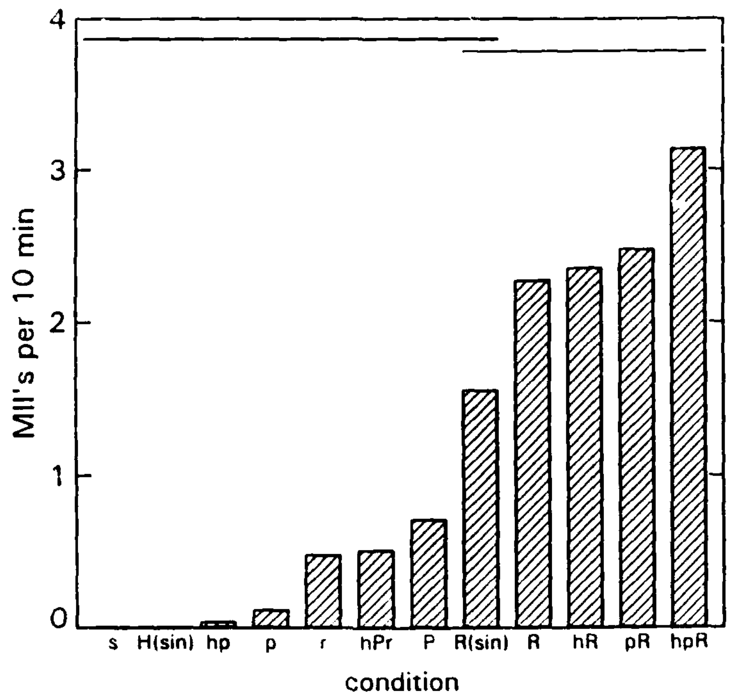

Fig. 6 Mean MII-score during different SMS movement conditions. Conditions connected with a horizontal line in the upper part of the figure, do not differ significantly from each other.

Fig. 6 illustrates that conditions with a *large roll* component generated significantly more MII's than conditions without or with only a small roll component. The only exception was condition R(sin), which had an MII score that fell between the mean MII values of the group of conditions without and with a large roll component. This is an interesting finding, because the large roll in condition R(sin) was the only predictable roll motion in the experiment. Hence it seems that if (relatively large) roll motions are predictable, they tend to have a somewhat smaller MII inducing potential.

We did not observe a significant main effect of, or interaction with, gender or any other anthropometric or biological characteristic (Table I) on the MII scores.

4 DISCUSSION

In this study significant effects were observed of particular platform motion on the energy expenditure of walking humans, and the same can be said of MII's.

With respect to the measures of energy expenditure, it was most noteworthy that conditions consisting either of just a large pitch motion, or of *both* a pitch and a roll component (either one of them being large), caused higher $\dot{V}O_2$, $\dot{V}CO_2$ and

$\dot{V}_E$ than conditions without pitch, or with a small pitch not accompanied by roll. However, when conditions consist of large roll motions only (whether or not accompanied by vertical motion), they still cause more energy expenditure than when they consist only of *small pitch and/or roll motions* (with or without vertical motion). The general picture, which emerges from this configuration of results is that energy consumption is most dependent on pitch. This is most likely due to the fact that subjects, who are required to walk on a platform which moves in pitch, must continuously walk up and down hill. The slight horizontal parasitical movements in pitch conditions may also have contributed to task load. Apparently this requires more energy than maintaining balance when walking on a platform that moves in roll, because pure roll conditions cause most MII's.

In the above mentioned earlier study on the effects of roll, pitch and vertical movements of the SMS (Wertheim et al., 1993) no difference in energy expenditure was observed between pitch-only and roll-only conditions (although pitch and roll were both more energy consuming than the vertical motion or the stationary control conditions). The reason for this discrepancy is most likely that in the earlier study the pitch and roll excursions were in general rather small (5° sinus motions) and more similar to the present p and r conditions (which do not either differ much from each other) than to the present P and R conditions (which differ much more from each other).

The present data are very interesting with respect to our measure of physiological workload. In the most demanding hPr condition (see Fig. 4) our subjects used about 31% of their maximum capacity for $\dot{V}O_2$ consumption, as compared to 24% in the stationary condition. Thus it may be concluded, that movements of the SMS as used in this study, already considerably increase our workload when we perform such a simple task as walking on a treadmill. This suggests that with more heavy tasks performance on a moving ship may indeed result in too large a work load: it is impossible to work longer than 2 hours at a task requiring more than 40% of $\dot{V}O_{2max}$ (Evans et al., 1980; Holewijn, 1989). If a particular task already requires around 40% of $\dot{V}O_{2max}$ when performed ashore, it may easily reach requirements of 50% or more of $\dot{V}O_{2max}$ at sea, especially at high sea states and with relatively small ships (e.g. coast guard). For continuous task performance this is definitely too demanding.

On the other hand, it might be possible that the increased task demand which results from ship movements, is specific only to the particular task of walking (that is, walking uphill or downhill, as happens during pitch movements of the SMS). Thus it is conceivable, that other tasks which include motor activity of a different kind—e.g. involving only head and arm movements—may be less affected. Answers to this question can only be given with further research (it should be noted here, that tasks which include the requirement to make head movements, may facilitate motion sickness, which might complicate the theoretical interpretation of measures of energy expenditure).

With respect to MII's the results are also interesting. The assumption that the higher energy consumption in roll and pitch conditions in the earlier experiment, may have resulted from a higher incidence of MII's is not supported. Most MII's are found in conditions with a large roll component. In fact, these are the only conditions which differ significantly from the stationary condition in terms of their MII score. This seems to be at odds with findings from Colwell at DREA laboratory in Canada (personal communication), based on an MII model developed there (Graham, 1990). According to that model pitch movements are more MII-inducing than roll movements. However, a closer look at the model reveals that it is based on subjects standing still (with their legs slightly apart) with the tips of their shoes touching a line drawn on the floor. The model then defines an MII as an instance of balance interference which leads to a recuperating forward movement of at least one foot across that boundary line. It is obvious that in such circumstances roll movements do not interfere much with balance, as both feet rest on the floor. In the present study subjects did not stand still with both feet resting on the floor, but walked, and roll movements of the SMS are by definition perpendicular to the direction of walking. As compared to more natural circumstances, walking on a surface that tilts sidewards is a rather unusual experience. In contrast, Pitch movements of the SMS resemble the more commonly encountered circumstance of walking up or down a slope, and humans are known to have little difficulty in maintaining good postural control when walking in pitch (Kapteijn, 1973), even though it may require more energy, as the present data show. Hence, our data illustrate that there is a need to extend the DREA-model for MII's, and make it applicable to postural control in dynamic situations.

The failure to replicate the observation from the earlier study, that pitch and roll movements cause higher heart rates than vertical motion and stationary conditions, is a somewhat surprising result. The only explanation is that the over all level of the heart rate scores was lower than in the earlier study. Usually heart rate scores have a close linear relation to ventilatory parameters, but the relation is likely to deteriorate below a heart rate of 120 beats$\cdot$min^{-1} (Åstrand & Rodahl, 1986; McArdle et al., 1991). The deterioration is probably caused by the fact that at low heart rates humans compensate for extra workload by elevating the heart's stroke volume (Bevegard et al., 1963; Damoto et al., 1966). This is what may have happened in the present study, because mean heart rate across all conditions was around 100 beats/min, while in the prior study it was over 110 beats/min. The higher heart rates in the prior study could have resulted from stress: in that study we did not use a mouth piece for conveying breathing air to the Oxycon apparatus (as in the present study), but a face mask consisting of an adapted military gas mask. Given the air tightness of the mask and its relatively restricted field of vision, wearing such a mask may well have caused some stress, elevating heart rate. This explanation is supported by the fact that RE levels, which do have some correlation to stress and hyperventilation, were also somewhat higher in the earlier study than in the present one.

Given these considerations, it seems that heart rate is a somewhat less reliable measure of energy consumption than the ventilatory parameters.

5 CONCLUSIONS

In general we can summarize the present results in the following main conclusions:

a. Walking requires significantly more energy on a moving platform than on a stationary environment.
b. Walking on a moving platform gives highest energy expenditure when platform motion includes at least a large pitch component, or a combination of pitch and roll components.
c. For this kind of research, ventilatory measures of energy expenditure are more appropriate than heart rate.
d. If platform motion includes a significant roll component, a notable increase in problems with postural control is likely to happen, but this does not necessarily cause as much of an increase in energy expenditure.

6 RECOMMENDATIONS FOR FURTHER RESEARCH

a. One question that now becomes of interest is whether the increased task demand for tasks carried out on a moving platform relates also to other tasks, i.e. tasks requiring less motor activity and more cognitive skills.
b. Another question is, whether adaptation occurs when subjects spend a much longer period in the SMS, resulting in a gradual return of energy expenditure to lower levels.
c. The latter question is rather complex, because it may well relate to research issues associated with motion sickness. The point is that a long stay in the SMS may cause motion sickness symptoms. We do not know to what extend (or even if) these symptoms correlate with energy expenditure. Neither do we know how such symptoms affect cognitive and/or motor tasks (although a certain degree of deterioration is likely to happen). In addition, here again questions of adaptation can be asked.

7 POTENTIAL APPLICATIONS

If such further research bears fruit, the methodology as developed here can be applied to provide an empirical database, which could be used to help establish acceptable standards for work load and safety during performance on various

tasks aboard ships at sea. Since such a database would include data on the relation between task load and the movements of the ship on which the task is carried out, it would be relevant to models used for assessing a ships' operability, at different sea states.

Such assessments are not only relevant for strategic planning (e.g. wargames). They are also relevant to ship design, where knowledge of ship operability criteria is linked to requirements about allowable tolerance limits of ship movement.

The application of the present methodology need not be restricted to task performance in a moving environment. It could be relevant to performance in other unusual environments as well (e.g. during heat strain). Another area of application is the measurement of task load in cases where the task is performed by humans with a handicap, wearing protheses.

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Soesterberg, 5 April 1994

Dr. A.H. Wertheim

APPENDIX A: Description of SMS motion parameters in all conditions
(see Table I for explanation of the condition codes)

Condition code: **hpR**

	Minimum	**Maximum**	**Average**	**RMS**
Vertical (m)	0.056	0.899	0.501	0.139
Pitch (deg)	-3.95	1.52	-1.18	0.88
Roll (deg)	-9.79	9.06	0.13	3.13
Vertical-Paras.$_{roll}$ (m)	-0.106	0.059	-0.008	0.028
Vertical$_{tot}$ (m)	0.039	0.909	0.493	0.149

Condition code: **H(sin)**

	Minimum	**Maximum**	**Average**	**RMS**
Vertical (m)	0.104	0.916	0.502	0.285
Pitch (deg)	-1.28	-1.13	-1.20	0.03
Roll (deg)	0.06	0.21	0.16	0.02
Vertical-Paras.$_{roll}$ (m)	0	0	0	0
Vertical$_{tot}$ (m)	0.104	0.916	0.502	0.285

Condition code: **p**

	Minimum	**Maximum**	**Average**	**RMS**
Vertical (m)	0.511	0.514	0.512	0.0004
Pitch (deg)	-3.95	1.52	-1.18	0.88
Roll (deg)	0.05	0.25	0.16	0.05
Vertical-Paras.$_{roll}$ (m)	0	0	0	0
Vertical$_{tot}$ (m)	0.511	0.514	0.512	0.0004

Condition code: **R**

	Minimum	**Maximum**	**Average**	**RMS**
Vertical (m)	0.512	0.513	0.512	0.0003
Pitch (deg)	-1.32	-1.14	-1.21	0.03
Roll (deg)	-9.79	9.06	0.13	3.13
Vertical-Paras.$_{roll}$ (m)	-0.106	0.059	-0.008	0.028
Vertical$_{tot}$ (m)	0.406	0.572	0.504	0.028

Condition code: **r**

	Minimum	**Maximum**	**Average**	**RMS**
Vertical (m)	0.510	0.513	0.512	0.0005
Pitch (deg)	-1.32	-1.14	-1.23	0.03
Roll (deg)	-2.56	2.85	0.16	0.84
Vertical-Paras.$_{roll}$ (m)	-0.032	0.017	-0.006	0.008
Vertical$_{tot}$ (m)	0.479	0.529	0.506	0.008

Condition code: **P**

	Minimum	**Maximum**	**Average**	**RMS**
Vertical (m)	0.510	0.513	0.512	0.0005
Pitch (deg)	-12.33	8.81	-1.21	3.51
Roll (deg)	-0.01	0.21	0.13	0.05
Vertical-Paras.$_{roll}$ (m)	0	0	0	0
Vertical$_{tot}$ (m)	0.510	0.513	0.512	0.0005

Condition code: **hp**

	Minimum	**Maximum**	**Average**	**RMS**
Vertical (m)	0.056	0.899	0.501	0.139
Pitch (deg)	-3.89	1.54	-1.16	0.86
Roll (deg)	0.02	0.18	0.12	0.03
Vertical-Paras.$_{roll}$ (m)	0	0	0	0
Vertical$_{tot}$ (m)	0.056	0.899	0.501	0.139

Condition code: **hR**

	Minimum	**Maximum**	**Average**	**RMS**
Vertical (m)	0.056	0.899	0.501	0.139
Pitch (deg)	-1.25	-1.09	-1.16	0.02
Roll (deg)	-9.79	9.06	0.13	3.13
Vertical-Paras.$_{roll}$ (m)	-0.106	0.059	-0.008	0.028
Vertical$_{tot}$ (m)	0.039	0.909	0.493	0.149

Condition code: **pR**

	Minimum	**Maximum**	**Average**	**RMS**
Vertical (m)	0.512	0.513	0.512	0.0003
Pitch (deg)	-3.95	1.52	-1.18	0.88
Roll (deg)	-9.79	9.06	0.13	3.13
Vertical-Paras.$_{roll}$ (m)	-0.106	0.059	-0.008	0.028
Vertical$_{tot}$ (m)	0.406	0.572	0.504	0.028

Condition code: **hPr**

	Minimum	**Maximum**	**Average**	**RMS**
Vertical (m)	0.096	0.873	0.503	0.124
Pitch (deg)	-12.26	8.81	-1.21	3.54
Roll (deg)	-2.55	2.84	0.16	0.87
Vertical-Paras.$_{roll}$ (m)	-0.032	0.017	-0.006	0.008
Vertical$_{tot}$ (m)	0.094	0.859	0.498	0.121

Condition code: **R(sin)**

	Minimum	**Maximum**	**Average**	**RMS**
Vertical (m)	0.511	0.515	0.512	0.0003
Pitch (deg)	-1.21	-0.27	-1.13	0.04
Roll (deg)	-4.42	4.63	0.07	3.21
Vertical-Paras.$_{roll}$ (m)	-0.051	0.030	-0.007	0.029
Vertical$_{tot}$ (m)	0.46	0.543	0.505	0.029

APPENDIX B: Order of presentation of simulator motion conditions for each subject.

Day	Subject no.											
	1	2	3	4	5	6	7	8	9	10	11	12
I	6	10	8	5	6	5	1	2	1	3	11	3
	3	2	5	7	10	2	3	7	6	4	4	12
	5	12	12	9	7	11	2	8	8	7	7	7
	8	1	6	8	4	3	5	1	3	11	3	8
	9	4	11	10	12	10	7	12	12	1	10	2
	12	8	4	3	1	7	11	9	11	5	2	10
II	10	5	2	1	2	9	4	4	2	8	5	1
	7	11	1	6	5	8	6	11	9	6	1	9
	11	9	7	2	8	1	8	3	10	10	8	5
	2	3	3	12	3	4	10	6	5	9	9	6
	1	7	9	11	9	12	12	5	7	12	6	4
	4	6	10	4	11	6	9	10	4	2	12	11

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Energy expenditure, physical work load and postural control during walking on a moving platform

11. AUTHOR(S)

A.H. Wertheim, R. Heus, and T.G.M. Vrijkotte

12. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

TNO Institute for Human Factors
Kampweg 5
3769 DE SOESTERBERG

13. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

TNO Defence Research
Schoemakerstraat 97
2628 VK Delft

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15. ABSTRACT (MAXIMUM 200 WORDS, 1044 BYTE)

An experiment was performed in which subjects were required to walk on a treadmill inside a moving ship motion simulator (SMS). Ventilatory measures of energy consumption, heart rate, and measures of postural control were taken and compared to a condition in which the SMS did not move. Eleven SMS movement conditions were investigated, two of which consisted of pure one dimensional sinusoidal movements (vertical motion or roll), two of simulated ship movements, and seven of various combinations of (large or small) vertical, pitch and roll movements, derived from these simulated ship motion profiles. The results showed that energy expenditure was largest in conditions which included either large pitch movements, or large roll components in combination with pitch. Energy expenditure was intermediate in all other conditions which included large roll movements. Effects of the particular vertical motions used in the present study, were not observed. In this particular study, physiological task load (expressed in terms of ventilatory parameters) was shown to increase on average with 15% during SMS movements. Heart rate appeared to be a less reliable measure of energy expenditure. Movement induced interruptions (MII's) of the walking task-a measure of postural control-were most frequent in conditions which included a large roll component. The relevance of this work with respect to the development of work load criteria at sea, for the estimation of a crew's operational capacity, and for ship building design are given, together with some recommendations for further research.

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